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ArF Excimer Laser Irradiation of Human Dentin

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Background and Objective: **The use of excimer lasers for treatment of dental hard tissues has considerable potential because the combined characteristics of low wavelength and short pulse result in limited heat diffusion and, therefore, tissue ablation without the problems of collateral damage. To date, there are relatively few published studies concerning the effects of excimer laser irradiation on dental hard tissues. Thus the present study was conducted to examine the morphological changes in tooth dentin subsequent to ArF excimer laser irradiation.**
Study Design/Materials and Methods: **The morphologic changes induced in normal, nondiseased human dentin following irradiation by an ArF excimer laser at fluences ranging from 1 to 4 J/cm^2 and the number of laser pulses ranging from 50 to 1,000 were evaluated by scanning electron microscopy.**
Results: **Two modes of ablation, photochemical at low fluences and thermal at high fluences, were observed. A fluence of 1 J/cm^2 when combined with 50 or 100 pulses produced a uniform ablation of the dentin surface without signs of tissue melting. At fluences >1.5 J/cm^2, the thermal mode of ablation was more efficient at removing intertubular dentin than peritubular dentin. Further, when compared to the lower fluences, the higher settings produced a rougher ablation crater surface. Additionally, the higher fluences produced surface melting with each pulse and sealing of exposed dentinal tubules after irradiation with 100–300 laser pulses.**
Conclusions: **The photochemical and thermal mechanisms of tooth dentin ablation were identified based on significant differences in tissue morphology following laser irradiation. The rates of tissue ablation and the observed morphologic changes indicate that the ArF excimer laser could be useful for caries removal and sealing of exposed dentinal tubules. Lasers Surg. Med. 21:474–479, 1997.**

Key words: dentin; ArF excimer laser; ablation; scanning electron microscopy (SEM)

INTRODUCTION

Laser irradiation is a powerful tool for the surface modification, drilling, and cutting of both biological and nonbiological materials. Laser applications for the treatment of soft tissue problems, such as incision and/or excision of lesions,

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are relatively common and often result in a less complicated convalescence. However, successful applications of lasers to dental hard tissue problems have been limited by the detrimental effects of irradiation, such as heat-induced surface cracking of enamel, dentin, and cementum and thermal necrosis of the pulp.

Numerous studies report the effects of different lasers on tooth enamel and dentin. Both continuous and pulsed lasers, ranging from picosecond to millisecond pulses, and wavelengths ranging from the ultraviolet, such as the excimer lasers [1–7], to the medium infrared, such as the CO_2 laser [8–9], have been used in these studies. Among lasers with pulse durations in the nanosecond range, the ultraviolet ArF excimer is attractive because of its very short 193 nm wavelength. At this wavelength, the absorption coefficient is very high for mineralized tissues. Given this combination of wavelength and short pulse duration, the energy produced by the ArF excimer laser is efficiently absorbed by only the most superficial layers of tissue. Consequently, due to the resulting low levels of heat diffusion, progressive ablation of the dental hard tissue can be effected without appreciable increases in pulpal temperature.

There is considerable interest in dentistry focused on the possibility of being able to substitute laser irradiation for the traditional mechanical means of caries removal. The ablation rate for carious regions, both in enamel and dentin, is greater than in nondiseased regions. Thus in theory, caries elimination could be accomplished without significant collateral damage to nondiseased tooth structure. Additionally, laser irradiation could effectively seal exposed dentinal tubules and thereby reduce the permeability of the dentinal layer. In this regard, several investigators have reported the effects of dental hard tissue ablation using the ArF excimer laser. For example, Neev et al. [2] examined changes in the morphology of both dentin and enamel and in tooth temperature using thermography under differing conditions of laser fluence and laser frequency. The authors noted the sealing of dentinal tubules and suggested that ablation rates were comparable to those obtained with other nanosecond pulsed lasers. Stabholz et al. [3] irradiated dentin to study the sealing of dentinal tubules. They noted melting of the mineral phase around the dentinal tubules, but sealing of the tubule openings was not observed. However, and possibly more important, large heat-induced cracks were seen in the irradiated tissue. Arima and Matsumoto [4], using low fluence, irradiated nondiseased and carious regions of both dentin and enamel and found higher ablation rates in the carious regions. Increases in tooth temperature were low and a high percentage of the exposed dentinal tubules was sealed in the nondiseased dentin, but not in the carious dentin. Collectively, these studies do not offer a complete impression of the effects of the ArF excimer laser irradiation on tooth dentin and enamel. In this report, we present our first results concerning the irradiation of nondiseased human tooth dentin by an ArF excimer laser. The induced changes in dentinal morphology after irradiation at different fluences using differing numbers of pulses are reported.

MATERIALS AND METHODS

Slices of tooth dentin, 3 mm thick, were obtained from freshly extracted, caries-free human molar teeth by transversal cuts above the pulp cavity. Prior to laser irradiation, the dentinal slices (specimens) were immersed in ethanol during 10–15 minutes to remove the debris. The individual specimens were glued to a holder and placed in a XYZ manipulator. They were irradiated with an ArF excimer laser beam with a pulse duration of 23 ns and a wavelength of 193 nm. A rectangular mask selected the homogeneous central part of the beam and was imaged with a lens system on the specimen target. Spots with dimensions ~0.4×1.0 mm^2 were obtained. Laser fluence was determined from the pulse energy measured with a pyroelectric energy meter and the spot area, and it ranged between 1 and 4 J/cm^2. The repetition rate was 5 Hz and the number of beam pulses were 50, 100, 300, and 1,000. Scanning electron microscopy (SEM) was used to determine the changes in dentin morphology and the ablation crater depth.

RESULTS

Dentin irradiated at a fluence of 1 J/cm^2 using 50 or 100 pulses exhibited a consistent and uniform pattern of ablation. The same rate of ablation was observed for both intertubular and peritubular dentin in most of the target area (Fig. 1). Despite the near threshold conditions, the ablation rate was relatively high, e.g., 0.36 μm per pulse in the crater shown in Figure 1. Under these conditions, the crater walls were noticeable sharp

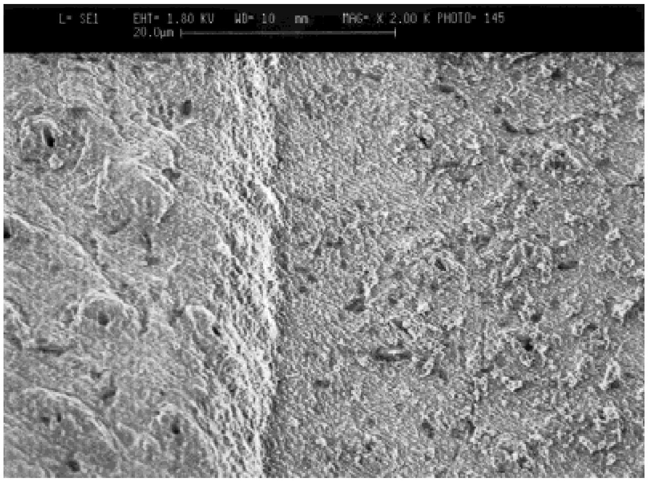

Fig. 1. SEM view (45°) of tooth dentin irradiated at 1.2 J/cm^2 with 50 pulses.

and well defined. There were no indications of melting of the mineral phase of the dentin, nor was there a noticeable transition between the irradiated and nonirradiated areas of tissue. However, the peritubular dentin of some tubules exhibited less of an ablation effect than did the intertubular dentin that resulted in elevations or "hills." Examination of the elevated areas at higher magnification revealed a partial sealing of the exposed tubules due to melting and resolidification of the mineral phase, although no signs of melting were observed in other target areas. The percentage of surface area in which a nonhomogeneous ablation was observed increased with fluence and the number of pulses.

At fluences close to 1.5 J/cm^2 and after 300 pulses, a different crater morphology is observed. There are local areas that were uniformly ablated (similar to Fig. 1), but ablation was nonhomogeneous in most of the target area (Fig. 2). The peritubular dentin around a high number of tubules was more resistant to irradiation than the surrounding intertubular dentin, and it resulted in the formation of hills (Fig. 2a). It is noticeable that the partial closure of the openings of these tubules is due to melting and resolidification of the peritubular dentin. These hills eventually assume a distinct cone-like configuration (Fig. 2b). The cones exhibit either totally or partially closed tubules at the vertex, whereas the cone base appears to cover one to several tubules. Two tubules can be observed on the lateral surface of the largest cone at the right side of Figure 2b.

At higher fluences, intertubular dentin was more efficiently ablated than peritubular dentin

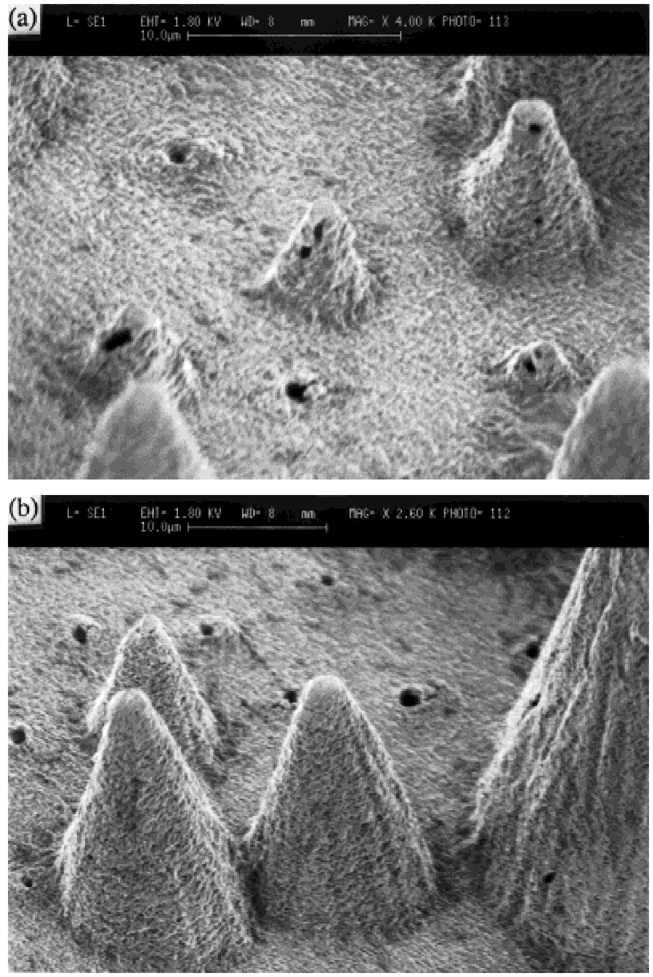

Fig. 2. SEM views (45°) of dentin irradiated at 1.5 J/cm^2 with 300 pulses: **(a)** area showing the early stage of hill development; **(b)** area showing cones. Note the open tubules on the surface of the largest cone.

in the whole target area, as can be seen in Figure 3, which shows a dentinal surface irradiated with 50 pulses at 2.6 J/cm^2. There appears to be a hill formation around individual tubules, in contrast to the larger more inclusive cones that form at fluences close to 1.5 J/cm^2. Individual tubules show a decrease in diameter and their margins clearly exhibit evidence of melting and resolidification (Fig. 3b). Examination of the crater walls also revealed evidence of melting and resolidification. By increasing the number of pulses from 50 to 100–300 resulted in sealing of practically all dentinal tubules (Fig. 4). Although the sealing efficiency appears to increase with the number of pulses, large cracks appear in the crater wall after 1,000 pulses (Fig. 5). The combination of high fluence and number of pulses produced well-defined ablation craters of 300–500 μm in depth. Such

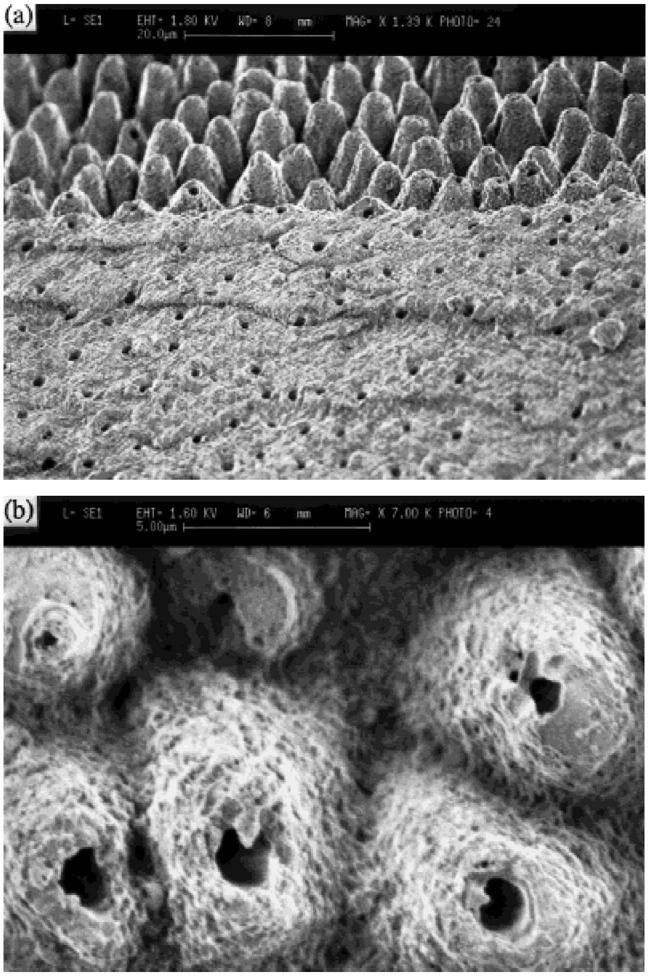

Fig. 3. SEM microphotographs of dentin irradiated at 2.6 J/cm^2 with 50 pulses: **(a)** 45° view of the border between irradiated dentin (top of photograph) and nonirradiated dentin; **(b)** 0° view of the crater floor. Note the signs of melting involving the peritubular dentin that produces a partial sealing of the tubules opening.

craters exhibited a distinct cubic shape with nearly vertical walls.

DISCUSSION

The present study suggests that both photochemical and thermal effects occur when human tooth dentin is irradiated with an ArF excimer laser. Photons at 193 nm have a high energy (6.3 eV) that is sufficient to ablate both intertubular and peritubular dentin by direct breaking of chemical bonds. At low fluence, photochemical effects are dominant and, as demonstrated in this study, the dentinal tubules are not sealed because peritubular dentin does not melt. Also, due to the

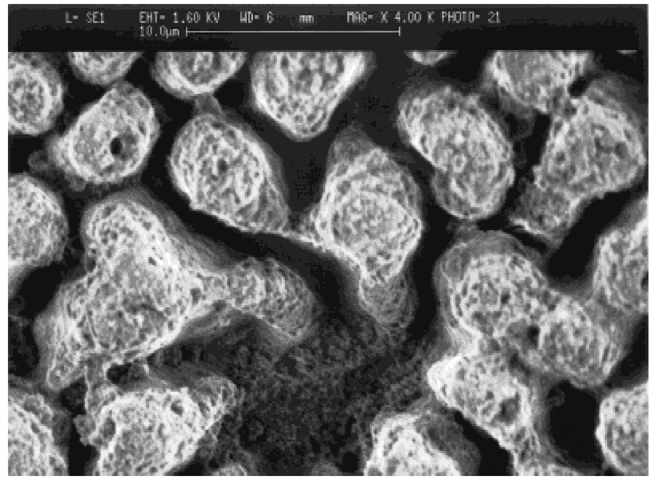

Fig. 4. SEM view (0°) of dentin subsequent to irradiation of 2.6 J/cm^2 with 100 pulses. Note that only the tubule opening of the upper left part remains unsealed.

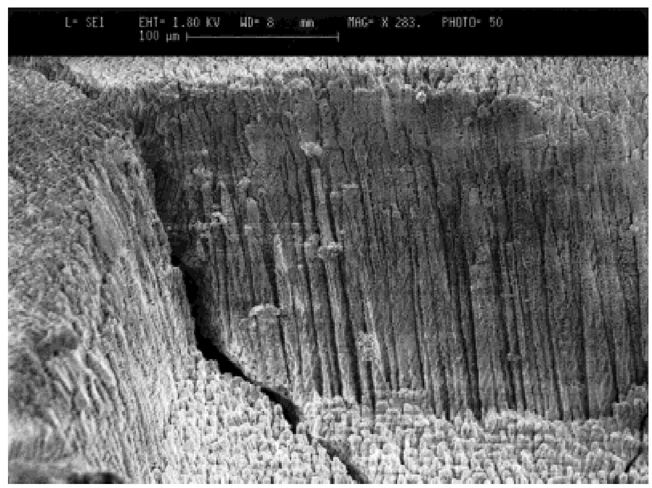

Fig. 5. SEM view (45°) of the wall and floor of the ablation crater following irradiation at 3.1 J/cm^2 with 1,000 laser pulses. Note the heat-induced large crack.

generalized effect of the laser at low fluence on both types of dentin, the floor of the ablation crater is relatively flat. A roughened surface topography was noted only in a few regions around tubules in which peritubular dentin had been less efficiently ablated. With continued irradiation, the rate of ablation in these regions was reduced because of the increase in surface area and, in second order, of reflectivity, a combination that resulted in a reduction in the effective fluence. This process, usually called dilution of fluence [10], is well known as one of the causes of cone formation by cumulative laser irradiation of targets of heterogeneous and even homogeneous

compositions [11]. Although the cone formations shown in Figure 2 have their origin in the non-uniform ablation, their development is not essentially determined by the heterogeneous chemical composition of dentin.

Irradiation of dentin using low fluence levels (photochemical ablation) does not induce melting and therefore the temperature increase is lower than that achieved when using high fluence settings for thermal ablation. In addition, it is to be noted that the rate of ablation at low fluence is only slightly less than the thermal ablation rate, and a greater surface area could be irradiated as the low fluence settings require a less focused laser beam. Consequently, the volume of tissue ablated per pulse may be comparable or even greater than that removed by thermal ablation mode using a high fluence.

The process of thermal ablation becomes more obvious as the fluence increases and, in the case of tooth dentin, is manifested by the formation of distinctive hills associated with the dentinal tubules. The bases of the hills do not extend on other tubules, and their development is likely due to the less efficient ablation of the hypermineralized peritubular dentin compared to that of the less mineralized intertubular dentin.

At the higher fluence settings, the dentinal tubules are sealed as a result of melting and resolidification of the peritubular dentin. However, thermal effects that produce the sealing also result in at least one detrimental effect, i.e., the occurrence of heat-induced cracking. In our case, cracking could be favored by a partial dehydration produced by the immersion in ethanol. Due to the cracking effect, it is not possible to seal all dentinal tubules, although the high percentage of those that are sealed undoubtedly has an effect on dentin permeability. It may be of potential clinical significance to note that sealing of dentinal tubules can be achieved after a relatively few number of pulses using a wide range of fluences.

Finally, it should be noted that the combination of low wavelength and short duration of the pulsed laser used in this study can generate target surface temperatures as high as several thousand Kelvin. However, such temperatures last for only microseconds after the pulsed exposure and are confined to only the most superficial regions of the target surface. Rapid melting of the target surface is then compatible with the low temperature increases measured after the pulsed exposure. Thus the effects of a high energy plasma on the floor and walls of the ablation crater may be minimal, unlike what has been suggested by Neev et al. [2,6] and Stabholz et al. [3,7].

In conclusion, this investigation on the changes in human tooth dentin following irradiation with an ArF excimer laser has provided information about the distinctive differences in morphology resulting from photochemical ablation at low fluences and thermal ablation at fluences >2 J/cm^2. Photochemical ablation at the low fluence settings resulted in craters of homogeneous morphology, a consistent rate of tissue ablation, and no indications of melting of the mineral phase of the dentin specimens. At higher fluence, the process of thermal ablation was less effective at removing the hypermineralized peritubular dentin than intertubular dentin and produced a crater floor characterized by a rough surface topography. Further, melting and resolidification of the peritubular dentin was noted, which resulted in sealing of the tubules. Based on the results of this study, it would appear that the ArF excimer laser could be useful for both the removal of dental caries and sealing of dentinal tubules.

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